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**Thermal Interaction of Contact Lens Eyewear and 94 GHz  
Ocular Exposures**

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## Naval Health Research Center Detachment Directed Energy Bioeffects Research Laboratory

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Technical Report – DEBL-2006-02

### **THERMAL INTERACTION OF CONTACT LENS EYEWEAR AND 94 GHz OCULAR EXPOSURES**

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## EXECUTIVE SUMMARY

### Background

Millimeter wave (MMW) hardware systems capable of generating high power MMWs have been developed for use as a non-lethal weapon system. This system, termed Active Denial System (ADS), uses a 94 GHz MMW beam to thwart an individual or group of individuals from advancing or entering restricted areas by causing rapid discomfort. Within seconds of the exposure, a targeted individual feels an intolerable skin heating sensation that stops when the transmitter is shut off or when the individual moves out of the MMW beam. The system was designed to produce rapid and intolerable skin heating. Natural behavior of a person experiencing such a sensation is to quickly escape the beam. The primary effect of the ADS is heating of the skin and eye by absorption of the 94 GHz millimeter waves.

### Objectives

In order to build safety features in the ADS and prevent permanent injury, the interaction between ADS exposure and a variety of intervening variables must be studied. Such variables include clothing and eyewear. Eyewear including eyeglasses, binoculars, riflescopes, and night vision goggles have been previously evaluated and found not to produce reflected hotspots of 94 GHz energy which might lead to higher skin and eye temperatures on the face and thus increase the risk of permanent injury. The objective of this study was to evaluate contact lens eyewear interaction with the 94 GHz MMW beam. This exploratory study was designed to investigate the thermal relationships between contact lens eyewear, worn by anesthetized non human primates and 94 GHz exposures and to address the risk of permanent injury.

### Approach

An infrared camera which could record temperature was used to evaluate 94 GHz heating. Two approaches were taken for this initial evaluation. First, several eyes removed from swine were fitted with hard or soft contact lenses and irradiated with 94 GHz MMW in the range of  $2 \text{ J/cm}^2$  to  $12 \text{ J/cm}^2$ . Several contact lens types were selected to represent the types of contacts lens worn world-wide. Both whole pig eyes and eyes prepared for modified Miyake-Apple view were used. The modified Miyake-Apple technique involves surgically removing the back half of the eye, the vitreous humor, and the crystalline lens. Thus, the IR camera could view the backside of the cornea from behind the eye to record thermal changes that transition through the cornea of the eye (Apple et al., 1990).

Second, four anesthetized non human primates, Rhesus Monkeys (*Macaca mulatta*) were used as subjects. The power density and duration of exposure of the 94 GHz exposures were chosen to produce a fluence of  $6 \text{ J/cm}^2$ . The 94 GHz exposures caused rapid heating which increased the surface temperature of the cornea and contact lens from baseline levels ( $\sim 32^\circ \text{C}$ ) to as high as  $56^\circ \text{C}$ . Exposures with or without contacts and sham exposures were the independent variable and cornea temperature was the dependent variable. Corneal temperature rise was recorded using an infrared (IR) camera. An optometrist examined the corneas before and after exposure.

### Results

The IR scans were converted to temperature showing the heating distributed across the monkey or swine cornea or through the swine cornea using the modified Miyake-Apple view. First, the heating rates with the porcine swine eyes were quite variable perhaps due to hydration of the eye prior to exposure. The most reliable data was gathered with porcine eyes that were hydrated prior to exposure with buffered saline. This data from the modified Miyake-Apple view did not show significant differences between exposures with and without contacts in heating of the cornea at lower levels of exposure. At higher levels of 94 GHz MMW exposure some differences between contacts and no contacts on heating of the cornea was observed.

Heating of the monkey cornea also did not show significant differences between heating with and without contact lenses. A mean maximum temperature of 56.15 °C ( $\pm 1.19$  °C) was observed when the cornea was exposed with a contact lens while a maximum temperature of 54.63 °C ( $\pm 1.15$  °C) occurred without the lens. The difference between baseline and maximum temperature of the cornea (Delta T) with and without contact lens on the cornea was not significant ( $t=2.12$ ,  $df=7$ ,  $P=0.07$ ). No unexpected corneal damage was observed when the monkey eye was exposed with a contact lens.

## Conclusions

This study was conducted to understand the thermal relationship between the potential for damage to the eye from ADS exposure and contact lens eyewear worn by individuals targeted by the ADS system. Will wearers of contact lenses be at greater risk for eye damage by brief 94 GHz exposures? In this study the thermal relationship between exposures to a 94 GHz MMW beam and contact lens on the cornea has been described. The results have shown that, under the conditions studied, the wearing of contact lenses during 94 GHz exposure does not pose a greater risk than not wearing contact lenses. In real life exposures, it is expected that alert individuals would blink, close their eyes, turn their head, and flee the MMW beam long before eye damage could occur from heating whether contacts were worn or not.

## **ABSTRACT**

The objective of this study was to evaluate effect on eye heating of contact lens eyewear exposed to a 94 GHz MMW beam. This study was designed to investigate the thermal relationships between contact lens eyewear and 94 GHz exposures. Enucleated swine eyes were evaluated using a modified Miyake-Apple technique which allowed IR images of the interior of the cornea to be taken while the front of the cornea was irradiated with and without contact lenses. Anesthetized Rhesus monkeys were also fitted with contact lenses and exposed to 94 GHz MMW. Significant differences between contacts and no contacts were not observed at low exposure levels ( $6 \text{ J/cm}^2$ ) for either porcine eyes or rhesus monkeys. At high exposure levels ( $12 \text{ J/cm}^2$ ) the swine eye data from the Miyake-Apple view did show significant differences in heating for contacts on the cornea compared to no contacts. Nevertheless, the results have shown that, under the conditions studied, the wearing of contact lenses during 94 GHz exposure does not pose a greater risk than not wearing contacts. In real life exposures it is expected that alert subjects would blink, close their eyes, turn their heads, and flee the MMW beam long before tissue damage could occur from heating whether contacts were worn or not.

## INTRODUCTION

The radio frequency (RF) portion of the electromagnetic spectrum includes nonionizing electromagnetic waves with frequencies in the range of 3 kHz to 300 GHz. The millimeter wave (MMW) frequency range is a subset within the RF region of the spectrum, comprising the frequency range from 30 to 300 GHz with wavelengths of 1 mm to 10 mm. Recently, hardware systems capable of generating high power MMWs have been developed for use as a non-lethal weapon system. ADS uses a 94 GHz MMW beam to thwart an individual or group of individuals from advancing or entering restricted areas. Traveling at the speed of light, the energy beam reaches the subject and penetrates less than 0.3 mm into the skin, quickly heating up the skin's surface. The system was designed to produce rapid and intolerable skin heating. Natural behavior of a person experiencing such a sensation is to escape the beam. The primary effect of the ADS system is heating of the skin and eye by absorption of the 94 GHz millimeter waves. Absorption and heating will occur at a rate determined by the power density of the millimeter wave beam at the surface of the tissue and the amount of energy reflected. At high power densities the heating rate will be rapid and discomfort achieved more quickly than at lower power densities. Uncomfortable sensations are closely tied to the actual skin and eye temperature. One of the goals of the biological effects research program has been to delineate the incapacitating effects of the ADS system from harmful thermal effects and to better define the risk of permanent injury. This is a dose-response question that may best be answered by evaluating the effects of 94 GHz MMW absorption on tissues starting with low power densities up to high power densities with controlled durations of exposure. To understand the effects of accidental overexposure to the ADS system, the thermal effects beyond the normal operating parameters must be studied. The thermal effects of ADS require detailed study because little scientific research has been done at MMW frequencies at high power levels for these short exposure durations. The potential for damage to the eyes from any proposed non-lethal weapon is an extremely sensitive issue. ADS weapon system operating characteristics should not cause permanent eye injury, vision impairment or irreversible injuries. In order to incorporate that safety feature, without unduly limiting the ADS weapon's effectiveness, system engineers must know the operational parameters that can cause such injury. ADS operating safeguards must be applicable to humans regardless of whether or not they have on eyewear or eye protection. Optimizing operational utility of ADS drives the need for systematic research. Recently, Chalfin et al., (2002) determined the minimal damage threshold of 94 GHz MMW to the monkey cornea to be  $5 \text{ J/cm}^2$ . The damage produced at this level of exposure healed within 24-48 hours with no permanent effects. An important feature of that study was to show the correlation between temperature increase and tissue damage. Chalfin et al., (2002) determined that for brief exposures the temperature rise associated with threshold minimal corneal injury was  $23^\circ\text{C}$  at the surface of the cornea. A thermal injury that would likely produce permanent changes in vision was investigated by Chalfin et al., (2005). In this study anesthetized rabbits were exposed to much higher fluence levels to produce irreversible corneal damage. The threshold temperature rise associated with this injury was  $50^\circ\text{C}$ .

In order to build in safety features to prevent permanent injury, the extent of eye tissue damage relative to 94 GHz exposures with and without contact lens eyewear must be known. This initial study was conducted to understand the relationship between ADS exposure and corneal heating with and without contact lens eyewear. Previous measurements of 94 GHz exposure and contact lenses had shown that hard contact lenses had a greater transmittance than soft flexible contact lenses (Dr. P. Grounds, Naval Research Laboratory, June 2003, personal communication). Because soft contact lenses are hydrophilic they may show greater heating than hard contact lenses. Thus, this exploratory study evaluated both hard and soft contact lenses. In the first experiment, enucleated porcine eyes were exposed with and without hard and soft contacts and temperature change recorded on the posterior aspect of the cornea inside the eye. In a second experiment, anesthetized nonhuman primates were exposed to a 94 GHz beam at power densities near ADS operating parameters. Corneal temperature was measured using a noncontact infrared camera during each exposure. Following exposure the thermal profile of corneal exposures with and without hard contact lenses fitted to the eyes were examined.

## MATERIAL AND METHODS

**Subjects for Experiment 1-** Enucleated eyes from adult Yucatan miniature swine were used for the initial experiment of this study. The eyes were removed from swine euthanized in a different research project and stored on ice for less than 3 hr prior to use on this study. Eyes were prepared for the modified Miyake-Apple view by skilled technicians under direction of an ophthalmologist (SC). The lens and surrounding fluid of the eye were removed. The front half of the eyeball, including the cornea, was fitted over the end of a plastic funnel so that the cornea was located in the small opening of the funnel. Care was taken to retain the original shape of the eyeball. This procedure allows the interior of the cornea to be viewed in the opening through the back of the eye. Thus, the temperature underneath the contact lens can be estimated from within the eye and not just from the front surface of the lens on the outside of the eye.

**Subjects for Experiment 2-** The subjects for the second experiment were 4 non human primates, rhesus monkeys (*Macaca mulatta*), ranging in age from 9 to 11 years old. Subjects were housed in a vivarium with automatic lights set to a 12-hour light/dark cycle. Ambient temperature in the vivarium was maintained between 68-72 degrees F. An automated monitoring system notified personnel if temperature ranges deviated from specifications. Formal approval to conduct these experiments was received from the Air Force Research Laboratory Animal Care and Use Committee at Brooks City-Base, TX (Navy Protocol 03-01). The monkeys were housed on Brooks City-Base in a standard vivarium environment, caged individually, and provided with environmental enrichment programs. The animals involved in this study were procured, maintained, and used in accordance with the Federal Animal Welfare Act and the "Guide for the Care and Use of Laboratory Animals," prepared by the Institute of Laboratory Animal Resources -- National Research Council.

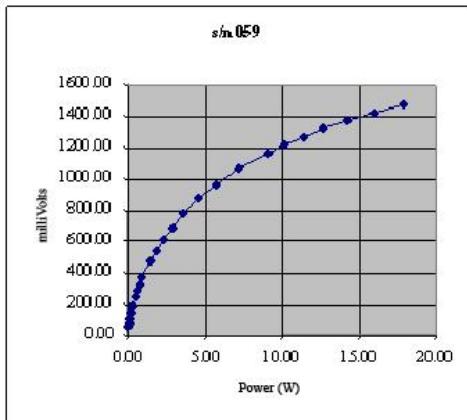
The rhesus monkey (*Macaca mulatta*) was used in this study because this species has proven to be a good surrogate for humans in many sensory experiments. For example, Harwerth, (1985) described the similarities which make the rhesus monkey a good model for visual capabilities of humans. They concluded that responses between the two species were very similar and that the neural systems responsible for visual information is fundamentally the same between the two species. Other studies have compared the visual systems of rhesus monkeys and humans and concluded that the rhesus monkey has nearly the same visual capabilities and is a good model for the human visual system.

## Apparatus-

**Contact Lenses For Both Experiments-** The contact lenses evaluated in this report were 1) hard (PMMA), 2) rigid (gas permeable; PPO2+, P18, F30, TA, CAB), and 3) flexible soft contacts. These lenses represent most of the world market in contact lens types.

**Millimeter Wave Exposure System for Experiment 1 Porcine Eye-** The exposure facility consisted of a 20' X 30' anechoic chamber. Inside the anechoic chamber a smaller 12' X 12' Styrofoam® environmentally-controlled room provided consistent temperature and humidity control. Exposures to energy densities ranging from 2 to 12 J/cm<sup>2</sup> were performed using a MMW exposure system in a far field exposure facility based on a coupled cavity traveling wave tube amplifier with an output of 800 W (North Star Research Corporation, Albuquerque, NM). The exposure setup consisted of 94 GHz standard gain horn with a built-in waveguide window to allow waveguide pressurization with SF6 gas. A dielectric lens was required to increase the power density above those produced by the standard gain horn antenna. A biconvex lens was selected for simplicity in design and machining (Shelton, et. al., 1991). The lens had a 16.31 cm (6.42 in.) radius and a 1.47 cm (0.58 in.) flange and was mounted in a wooden frame to ensure durability and stability. The output of the horn was aligned to the 94 GHz focusing lens. The lens surface was positioned 85 cm from the front surface of the standard gain horn. The focus point, at the output side of the lens, was 190 cm. This positioning provided a beam diameter, at the porcine cornea, of approximately 2 cm.

Measurements of field power density were done at the lens focal point using a crystal detector (Millitech DXP-08). The following technique was used to measure the power density in the exposure field. The initial step was to standardize the crystal detector by measuring the output voltage as compared to the input power. The output of the detector is non-linear, so numerous steps are measured across the range of the detector from threshold to saturated. The results are plotted as



shown in Figure 1.

Figure 1. Calibration of the crystal detector (mV) used to measure field power density.

The crystal detector was mounted on a three-axis precision manipulator for accurate scanning (millimeter resolution). The crystal detector was unable to handle 100% of the power at the point of interest so additional attenuation was required to protect the detector. The in-field measuring probe consisted of: 1) Crystal Detector, 2) 20.82 dB attenuator, 3) 11.24 dB 10W attenuator, and 4) Open Ended waveguide 16 cm long (13.01 dB of attenuation). The initial step of power measurement was to locate the center of the beam. Using an IR camera and carbon loaded Teflon sheet, the beam was located and marked on the IR camera's monitor (AOR). The Teflon was removed and the detector and 3-axis manipulator stand was placed in the field and aligned using the IR equipment. The transmitter was set to operate at 1Hz and energized. Using the 3-axis manipulator the probe was adjusted vertically and horizontally until the peak voltage out was indicated thus showing the center of the beam. The acquired voltage-out measurement was used in the following formula to calculate the field's power density.

Example:

The voltage out of the crystal was 1220mv.

1220mv from the crystal correlates to 10.19W.

The attenuation total was  $20.82+11.24+13.01 = 45.07$  dB of attenuation.

Attenuation was converted to gain.  $10^{(45.07/10)} = 32136.6$

Power \* gain = Peak power density.  $10.19 * 32136.6 = 327471.95$  mW/cm<sup>2</sup> peak

mW/cm<sup>2</sup> Pk \* $10^{-6}$  \* Pulse width = power density /pulse.

$327471.95 * 10^{-6} * 199.5 = 65.30$  mW/cm<sup>2</sup> per pulse

Power output of the MMW oscillators was controlled by manipulating the duty cycle (ratio of pulse-on time to pulse-off time) of a 1 kHz rectangular wave pulse train that gated the output of the oscillators. Pulse durations (50–500 µs) to produce the required duty cycles (5–50%) were calculated by a computer (Micron, 233 MHz, Micron Technology, Inc., 8000 S. Federal Way, PO Box 6, Boise, ID 83707-0006) and sent to a programmable function generator (HP 8116A) that produced pulse trains with the required time duration, to produce the desired energy density at the focal point of the lens.

**Millimeter Wave Exposure System for Experiment 2 Nonhuman Primate -**  
A magnetron (Model VKB2463L2, Communications & Power Industries BMD, Beverly, MA) was used to amplify the output of a mechanically-tunable Gunn oscillator (Model QTM-9517SW, QuinStar Technology, Inc., Torrance, CA). A Coolflow CFT-33 refrigerated recirculator (NESLAB, Portsmouth,

NH) was used to keep the magnetron cooled to 21°C. An open-ended waveguide (WR-10) was used to deliver the source output to the surface of the cornea. A programmable attenuator (Model 511W, Millimeter Products, Inc., Torrance, CA) was used to control the output of the mechanically-tuned Gunn oscillator. Power measurements were collected and recorded using a Hewlett Packard 437B power meter and a Hewlett Packard W8486A power sensor (Hewlett Packard, Houston, TX). Exposures were computer (Micron, Inc, Nampa, Idaho) controlled using a locally produced program written in Labview 7 Express (National Instruments, Austin, TX). The program controlled the MPI programmable attenuator and pulse duration as well as recording the output power from the Hewlett Packard 437B power meter. The exposure facility consisted of a 5 m X 5 m X 3 m high anechoic chamber.

**Surface Temperature Measurements-** A Flir System Model S60 infrared camera (Flir Systems, Boston, MA) was used to collect the temperature data for both experiments. ThermaCAM Researcher 2.7 IR software was used to control the camera and acquire image data. The IR camera was set to collect data at a rate of 60 frames per second. A start signal for infrared image collection was provided by the computer that controlled the MMW source. Thermal images were collected during 94 GHz exposures with relative ease. Some images were lost due to failure to trigger the camera or faulty storage disks. This issue was resolved with better cable shielding and not reusing storage media. The IR software, mentioned above, was used to measure temperature of the IR images. In each frame an area of interest could be set and the maximum temperature in that area could be recorded. For this study the area of interest was set to include the cornea of the eye as well as the area occupied by the contact lens in the image. An external calibration for the Flir S-60 camera was performed using a black-body source (Mikron, Model M340, Mikron Instrument Company, Inc., 16 Thornton Road, Oakland, NJ 07436). Most images were collected with the camera placed on a tripod to one side of the feed horn at an angle that allowed the most direct and unobstructed view of the monkey cornea during exposures. The software for the camera was used to measure temperature of the IR images.

## Procedures-

**Experiment 1: Porcine Millimeter Wave Eye Exposures-** Several porcine eyes were individually placed in the anechoic chamber and exposed multiple times to 94 GHz MMW at fluences of 2 J/cm<sup>2</sup>, 4 J/cm<sup>2</sup>, 6 J/cm<sup>2</sup>, or 12 J/cm<sup>2</sup> for 1 to several seconds. Between each exposure sufficient time was allowed for the eye to return to within 1-2 °C of its starting baseline temperature before another exposure. The eye was placed in the chamber, at the 190 cm focus point. The Infrared camera was located behind the eye and funnel, facing the large funnel opening, to measure heat transfer through the cornea. Before beginning exposures, the eye was moisturized with eye wetting solution (Bausch & Lomb). Prior to exposure a soft or hard contact lens was carefully fitted to the eye.

**Experiment 2: Nonhuman Primate Millimeter Wave Exposures-** The anesthetized subject was placed supine on a specially constructed cradle on top of an adjustable table. Vertical and horizontal movement of the table allowed precise positioning of the eye in relation to the source waveguide. The open-ended waveguide (OEW) at the eye was vertically polarized. One eye of each subject was positioned 1 cm from the OEW and exposed to CW 94 GHz MMWs at a fluence of 6 J/cm<sup>2</sup> with the other eye serving as a control. The eye to be exposed was anesthetized with one drop of 0.5% proparacaine HCl (Ophthetic, Allergan, Inc., 2525 Dupont Drive, PO Box 19534, Irvine, CA 92623). A wire lid speculum (E4106 H, Storz) was inserted immediately prior to the exposure, and the apex of the subject's cornea was positioned precisely 1.0 cm from the end of the waveguide. Immediately following the exposure the lid speculum was removed, allowing eyelid closure. Sham exposures, with and without contact lenses, were also conducted. Post exposure assessments for corneal damage were performed prior to exposures and 30 min following the exposure by the optometrist. Sham exposures were done in exactly the same manner as the MMW exposures except that the MMW source was not energized.

**Statistical Analysis-** To investigate the relationship between the independent (contact vs no contact) and dependent (corneal temperature) variables, each data set was graphed using the SIGMAPLOT version 8.0 program (SPSS 1998, SPSS, Inc., 233 S. Wacker Drive, Chicago, IL 60606). Students t-test for correlated data was used to detect overall significant differences between contact and no contact heating. Temperature change across time was collected from each IR image frame and plotted to show the rate of heating during exposure and the cooling curve after the exposure had ceased. This data was subjected to repeated measures analysis of variance (RMANOVA) using SYSTAT, version 11 (SPSS 1999, SPSS, Inc., 233 S. Wacker Drive, Chicago, IL 60606).

## RESULTS

**Experiment 1 Porcine Eyes-** A total of 21 exposures were collected for the four porcine eyes. The objective was to determine if the heating of the cornea, produced by 94 GHz MMW exposure, was greater with a contact compared to no contact. One exposure run was lost due to the IR camera failing to trigger during the exposure. Multiple IR images (20 frames per sec) were collected during each exposure and temperature change data was plotted. The hard contacts were much easier to keep on the eye while the soft contacts were not. Numerous times the soft contact would not adhere well to the eye and its position over the cornea was difficult to maintain. The results of these measurements are shown in Figures 2-5. These show the heating rate of 94 GHz MMW at four different fluences on the inside surface of the cornea. The thermal measurements were taken on the inside of the cornea through an opening at the back of the eye (Miyake-Apple view). Heating was somewhat delayed due to the thermal transit time through the cornea. Heating with the first eye, exposed at  $2 \text{ J/cm}^2$ , is shown in Figure 2 where the exposures were done with no contact or either a hard contact or soft contact. The temperature increase of the cornea without a contact was  $2.9^\circ\text{C}$ , hard contact  $3.4^\circ\text{C}$ , and  $2.9^\circ\text{C}$  for the soft contacts. The soft contact, contrary to expectation, produced less heating than the hard contact. There was not a significant difference in heating between contacts and no contacts at this level of exposure.

The second eye was exposed multiple times at a fluence of  $4 \text{ J/cm}^2$ . Heating on the eye was measured with and without hard contacts. This result is shown in Fig. 3 in which the overall temperature increase was  $5.01^\circ\text{C}$  ( $\pm 0.06^\circ\text{C}$  SEM) without the contact and  $5.26^\circ\text{C}$  ( $\pm 0.20^\circ\text{C}$  SEM) with the contact. Heating was increased, compared to  $2 \text{ J/cm}^2$ , but the difference in heating between contacts versus no contacts was minimal. Exposure at  $6 \text{ J/cm}^2$  produced a similar outcome of  $14.97^\circ\text{C}$  ( $\pm 0.34^\circ\text{C}$  SEM) temperature increase without a contact and  $15.40^\circ\text{C}$  ( $\pm 0.84^\circ\text{C}$  SEM) temperature increases for exposure with a contact (see Fig. 4). At a fluence of  $12 \text{ J/cm}^2$  the average temperature increase was  $17.85^\circ\text{C}$  ( $\pm 0.32^\circ\text{C}$  SEM) for no contact and  $20.89^\circ\text{C}$  ( $\pm 0.58^\circ\text{C}$  SEM) for exposures with a contact (see Fig. 5).

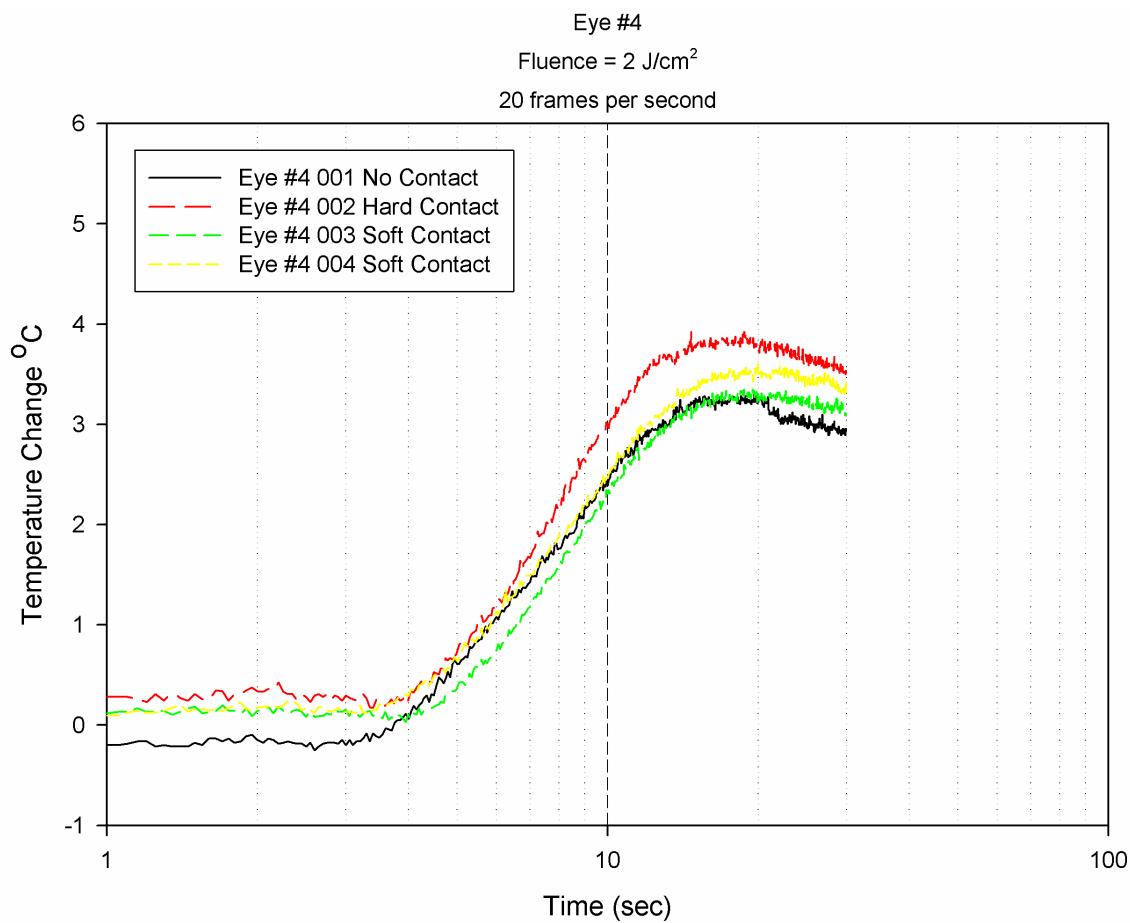


Figure 2. Miyake-Apple view of Porcine eye exposed several times with hard and soft contacts to 94 GHz MMW at a fluence of 2 J/cm<sup>2</sup>.

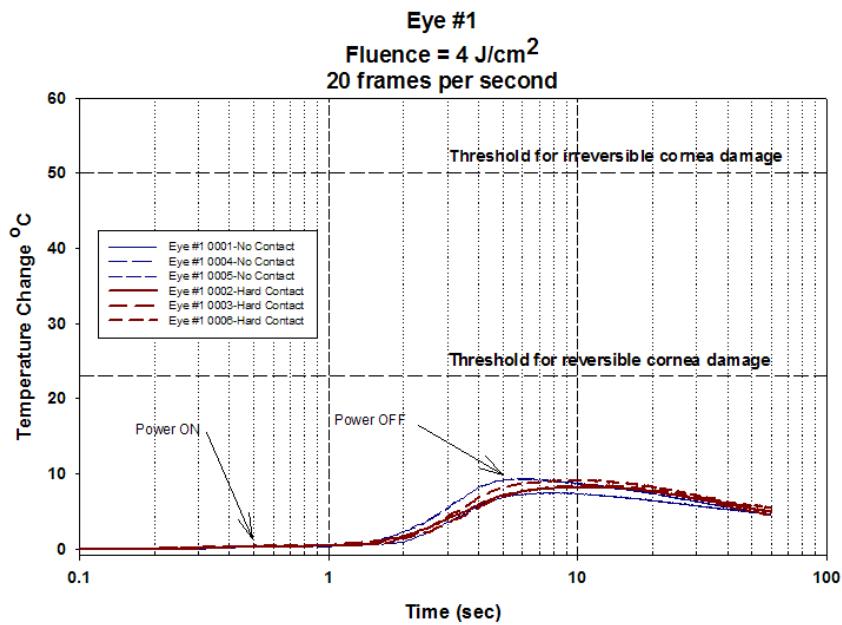


Figure 3. Miyake-Apple view of Porcine eye exposed several times with and without hard contacts to 94 GHz MMW at a fluence of  $4 \text{ J/cm}^2$ . Thresholds for reversible and irreversible cornea damage are shown (Chalfin et al., 2002; Chalfin et al., 2005).

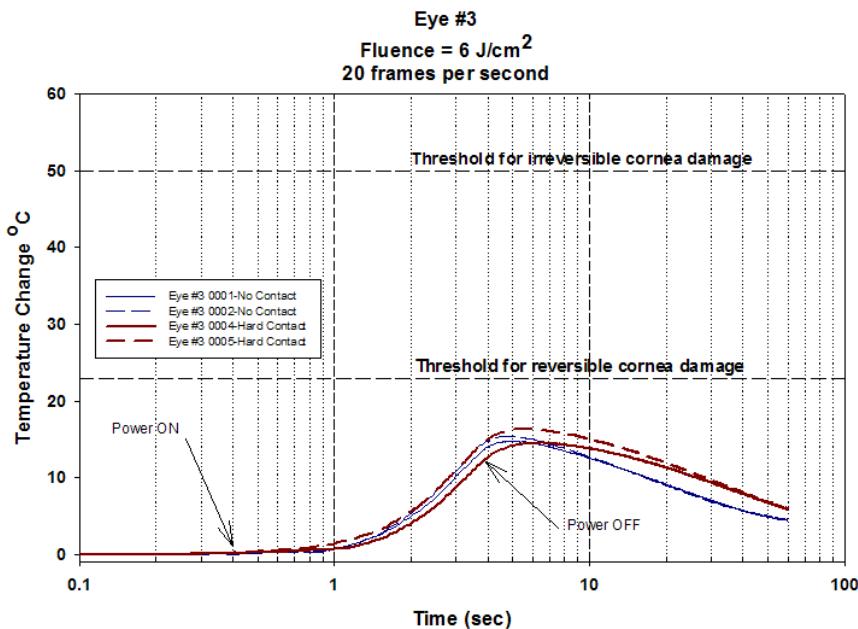


Figure 4. Miyake-Apple view of Porcine eye exposed several times with and without hard contacts to 94 GHz MMW at a fluence of  $6 \text{ J/cm}^2$ . Thresholds for reversible and irreversible cornea damage are shown (Chalfin et al., 2002; Chalfin et al., 2005).

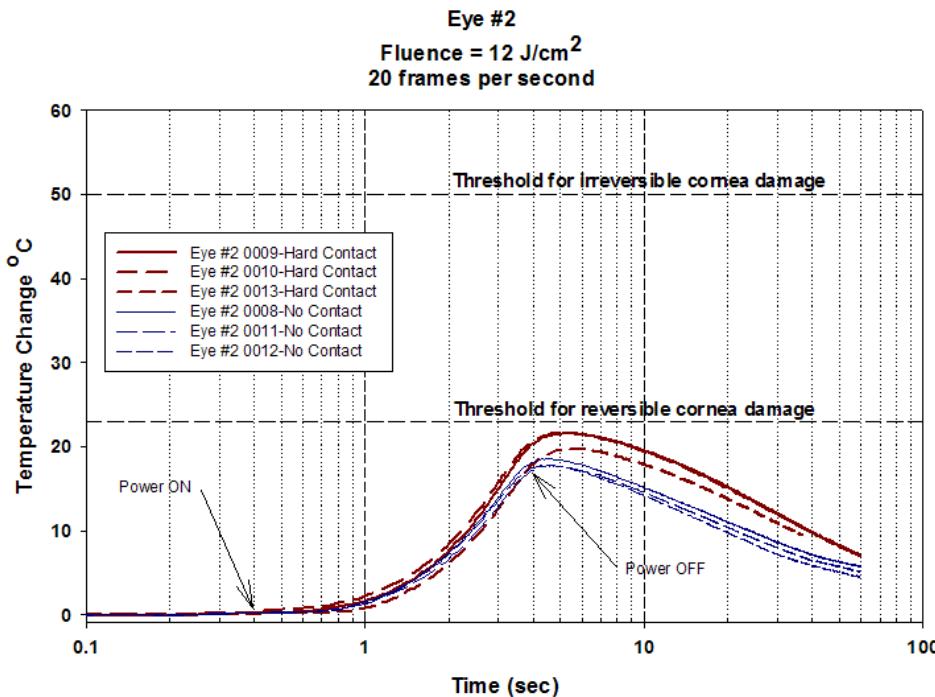


Figure 5. Miyake-Apple view of Porcine eye exposed several times with and without hard contacts to 94 GHz MMW at a fluence of  $12 \text{ J/cm}^2$ . Thresholds for reversible and irreversible cornea damage are shown (Chalfin et al., 2002; Chalfin et al., 2005).

**Experiment 2 Nonhuman Primate Eye Exposure-** A total of 32 exposures with anesthetized nonhuman primates were conducted with and without hard contact lenses (including sham exposures). The independent variable was the presence or absence of a hard contact lens and corneal temperature was the dependent variable. Temperature calibrated images of the cornea, taken by the infrared camera for each monkey exposure, were scanned and temperatures across the corneal image were computed. Pre-exposure and post-exposure maximum temperatures in each image were also recorded. This data is listed in Table 1. Sham exposures to 94 GHz, both with and without a hard contact lens fitted to the eye, are shown in the top half of the table. Exposures to 94 GHz, both with and without a hard contact lens, are shown in the lower half of the table. Sham exposures caused little to no temperature change on the surface of the cornea. The 94 GHz exposures at a fluence of  $6 \text{ J/cm}^2$  caused prompt heating on the surface of the cornea and the contact lens. The heating abruptly stopped when the exposure ceased. A maximum temperature of  $56.15^\circ\text{C}$  ( $\pm 1.19^\circ\text{C}$  SEM) was observed when the cornea was exposed with a contact lens while a maximum temperature of  $54.63^\circ\text{C}$  ( $\pm 1.15^\circ\text{C}$  SEM) occurred without the lens. This difference between maximum temperature of the cornea with and without contact lens on the cornea was not significant ( $t=1.19$ ,  $df = 7$ ,  $P>0.5$ ). No unexpected corneal damage was observed when the monkey eye was exposed with a contact lens. An example of temperature change on the cornea before, during, and after a single exposure to  $6 \text{ J/cm}^2$  with and without hard contact lenses is shown in Fig. 5. Temperature rise and fall occurred rapidly, as most of the 94 GHz energy is either reflected or absorbed. The absorbed energy is distributed within the first 0.336 mm of the cornea (Gandhi and Riazi 1986).

Table 1. Pre and post exposure data for contact lens exposure ( $6 \text{ J/cm}^2$ ) of anesthetized rhesus monkeys.

Sham Exposure WO Contact			Sham Exposure With Contact				
	Start °C	End °C	Delta T		Start °C	End °C	Delta T
	32.20	32.20	0.00		32.60	32.80	0.20
	30.80	30.90	0.10		32.70	32.90	0.20
	31.70	31.70	0.00		32.30	32.50	0.20
	32.00	32.00	0.00		32.00	32.00	0.00
	32.70	33.00	0.30		32.10	32.20	0.10
	32.00	32.00	0.00		31.50	31.90	0.40
	34.10	34.10	0.00		32.50	32.60	0.10
	32.40	32.40	0.00		32.50	32.60	0.10
Mean	32.24	32.29	0.05	Mean	32.28	32.44	0.16
Median	32.10	32.10	0.00	Median	32.40	32.55	0.15
SD	0.94	0.95	0.11	SD	0.40	0.37	0.12
SEM	0.33	0.33	0.04	SEM	0.14	0.13	0.04

94 GHz WO Contact			94 GHz With Contact				
	Start °C	End °C	Delta T		Start °C	End °C	Delta T
	33.60	53.40	19.80		32.10	57.20	25.10
	31.70	50.80	19.10		31.50	51.50	20.00
	31.60	52.30	20.70		31.80	56.90	25.10
	30.90	52.10	21.20		30.30	59.80	29.50
	33.00	59.70	26.70		31.30	58.90	27.60
	34.00	59.10	25.10		30.80	52.10	21.30
	34.20	55.20	21.00		31.40	53.40	22.00
	33.30	54.40	21.10		31.80	59.40	27.60
Mean	32.79	54.63	21.84	Mean	31.38	56.15	24.78
Median	33.15	53.90	21.05	Median	31.45	57.05	25.60
SD	1.23	3.25	2.64	SD	0.58	3.35	2.77
SEM	0.43	1.15	0.93	SEM	0.21	1.19	0.98

The mean heating across time for the 32 exposures with and without a contact lens is shown in Figure 6. The temperature increase over the duration of the exposures with and without a contact was significant but the heating for contact and no contact conditions was not significant. The interaction between contact and exposure was not significant for a conservative test. The results of the RMANOVA are shown in Table 2.

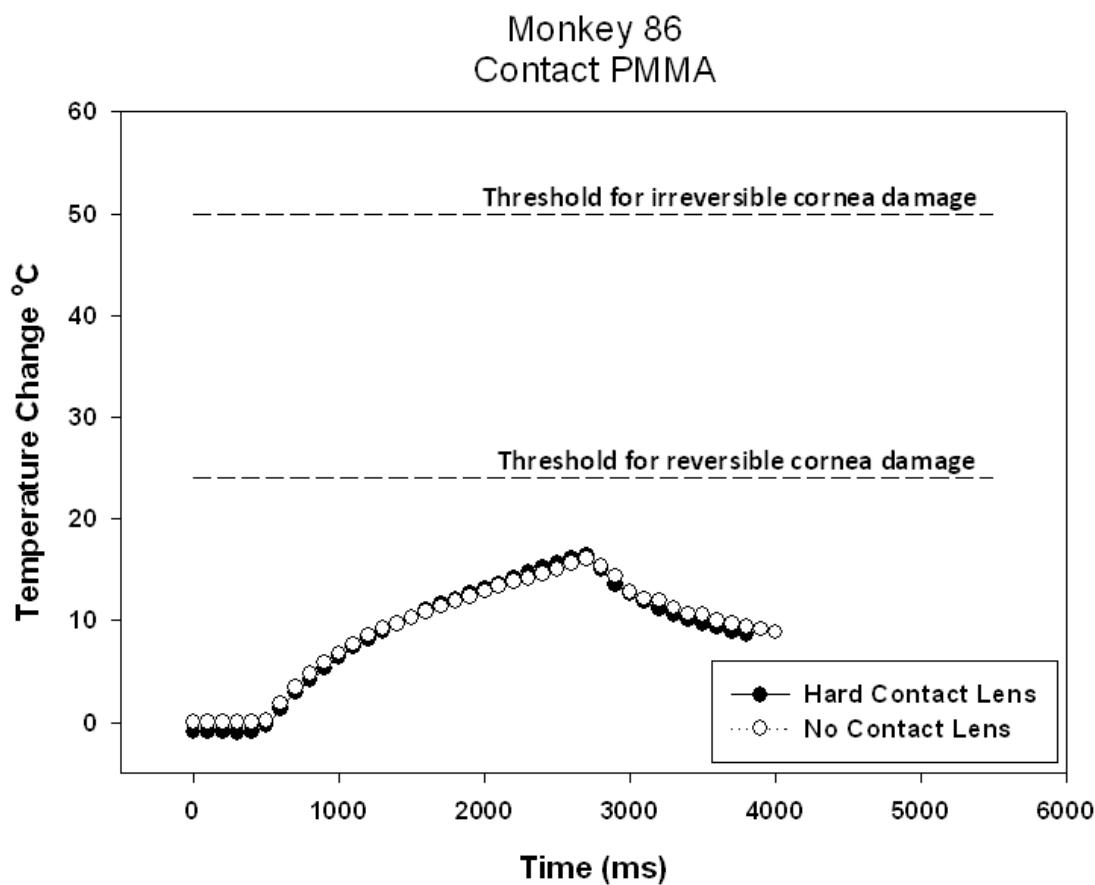


Figure 6. Maximum temperature profile during exposure ( $6 \text{ J/cm}^2$ ) of monkey cornea to 94 GHz MMW with and without a rigid (PMMA) hard contact lens on the eye. Thresholds for reversible and irreversible cornea damage are shown (Chalfin et al., 2002; Chalfin et al., 2005).

## Contact Lens Summary Non Human Primate Exposures

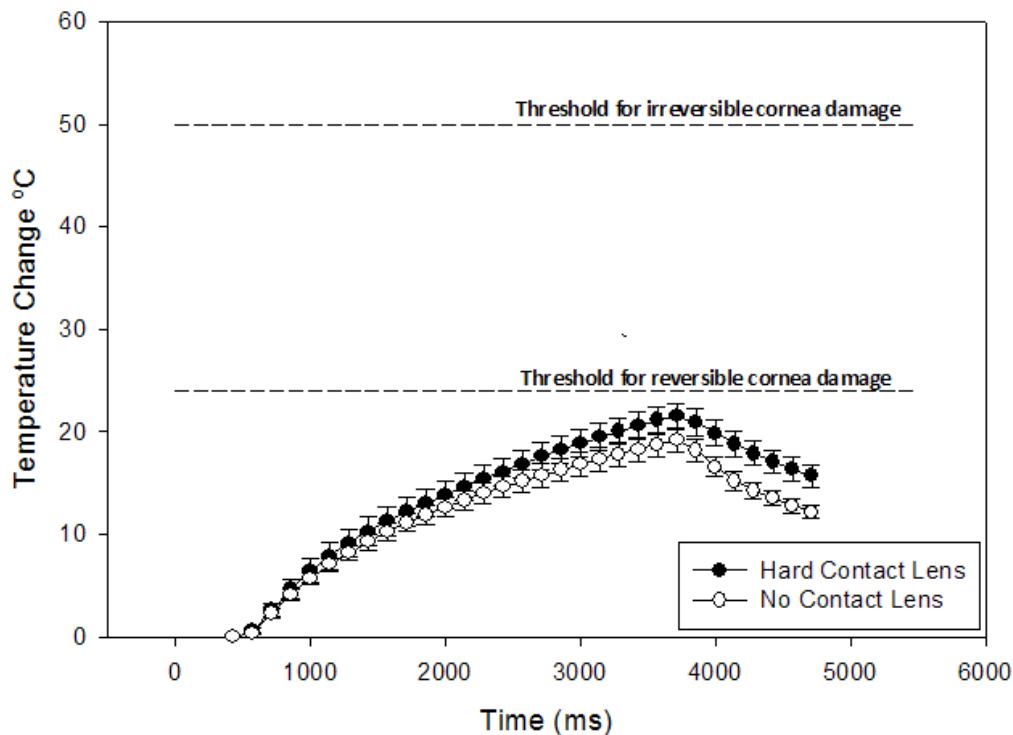


Figure 7. Maximum corneal temperature change during exposures ( $6 \text{ J/cm}^2$ ) with and without contact lens. Thresholds for reversible and irreversible cornea damage are shown (Chalfin et al., 2002; Chalfin et al., 2005).

Table 2. Univariate Repeated Measures Analysis for nonhuman primate exposures.

Between Subjects

Source	SS	df	MS	F	P
Contact/No Contact	493.196	1	493.196	2.152	0.164
Error	3208.069	14	229.148		

Within Subjects

Source	SS	df	MS	F	P	G-G	H-F
Time	26292.088	38	691.897	314.979	0.000	0.000	0.000
Cont*time	242.967	38	6.394	2.911	0.000	0.071	0.056
Error	1168.616	532	2.197				

Greenhouse-Geisser Epsilon: 0.0530  
Huynh-Feldt Epsilon : 0.0664

## **DISCUSSION**

The ADS will deliver human MMW exposure as a non-lethal weapon. The operational use of the ADS will result in MMW exposures that will include exposure of the eyes. Therefore studies of corneal response to ocular MMW exposures are important prior to its fielding as a non-lethal weapon. Ocular exposures from ADS will result in most of the 94 GHz energy being deposited in the first 0.3 mm of the cornea. Thus, 94 GHz exposure does not reach the lens or retina of the eye. The reason for conducting this study was to provide additional data from which the margin of safety between effectiveness and injury by ADS could be better defined. Previous research has determined the facial detection and aversion thresholds as  $3 \text{ mJ/cm}^2$  and  $0.4 \text{ J/cm}^2$ , respectively (D'Andrea et al., 1999 and 2004). The research conducted by Chalfin et al., (2002) defined the threshold for a minimal lesion (faint epithelial edema and fluorescein staining) at  $5\text{-}6 \text{ J/cm}^2$ . The lesions reported by Chalfin et al., (2002) are distinct, involve only the superficial epithelial layers of the cornea, and are reversible within 24-48 hours. In a recent study by Chalfin et al., (2005) we observed a  $27.7 \text{ J/cm}^2$  threshold of irreversible injury using a clinical observation scale and a  $29.5 \text{ J/cm}^2$  threshold based on microscopic evaluation of corneal tissue using a scale defined by tissue necrosis. These levels of energy density are the threshold for irreversible corneal tissue injury which possibly would produce significant scarring and loss of some vision.

The results presented in this report show that subjects wearing contact lenses do not exhibit a significantly higher corneal temperature relative to not wearing a contact lens (see Table 2, contact x time interaction,  $F_{38, 532} = 2.91$ , NS). The soft contact lenses evaluated here do not seem to heat at a greater rate than the hard contacts. Thus, there is not a greater risk for injury when wearing contact lenses. It is important to note that the level of corneal heating reported in this study would not likely occur if the non human primates were awake and alert, as protective reflexes of eye blink and head turning would stop the exposure to lessen heating and prevent corneal damage from occurring.

## **CONCLUSION**

This research study is one part of an overall plan which covered issues of effectiveness, safety margins for skin and eye thermal injuries, legal, policy, and public acceptability, and an initial evaluation of military utility. The results of this study when taken with the previous research by D'Andrea et al., (1999, 2004) and Chalfin et al., (2002, 2005) show that 94 GHz exposures produce responses which are time and temperature dependent. Effects on the eye are highly dependent on energy density and, because the effective stimulus is joule heating, exposure duration is very important. The uncomfortable sensations produced by the ADS system are closely tied to cornea and skin temperature. This study showed that wearing contact lens corrective eyewear should not significantly increase the risk of injury. The ADS has a very good margin of safety to prevent serious injury under which to operate as a non-lethal weapon.

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